

---

# Marine Physical Laboratory

## Measurements of Wave Breaking and Dissipation over the Continental Shelf

W. Kendall Melville

Supported by the  
Office of Naval Research  
Grant Number: N00014-97-1-0277

Final Report

June 2003

**DISTRIBUTION STATEMENT A**  
Approved for Public Release  
Distribution Unlimited

University of California, San Diego  
Scripps Institution of Oceanography

---

20040809 096

REPORT DOCUMENTATION PAGE			Form Approved OMB No 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.</small>				
1. Agency Use Only (Leave Blank).		2. Report Date. June 2003		3. Report Type and Dates Covered. Final Report
4. Title and Subtitle. <b>Measurements of Wave Breaking and Dissipation over the Continental Shelf</b>			5. Funding Number. N00014-97-1-0277	
6. Author(s). W. Kendall Melville			Project No. Task No.	
7. Performing Monitoring Agency Name(s) and Address(es). University of California, San Diego Marine Physical Laboratory Scripps Institution of Oceanography 291 Rosecrans Street San Diego, CA 92106			8. Performing Organization Report Number.	
9. Sponsoring/Monitoring Agency Name(s) and Address(es). Office of Naval Research Department of the Navy 800 North Quincy Street Arlington, VA 22217-5660 Attn: Dr. Louis Goodman, Code 322PO			10. Sponsoring/Monitoring Agency Report Number.	
11. Supplementary Notes.				
12a. Distribution/Availability Statement.  Approved for public release; distribution is unlimited.			12b. Distribution Code.	
13. Abstract (Maximum 200 words).  The objectives of this project were to develop and use remote and in situ techniques to measure the kinematics and dynamics of breaking and relate them to the dynamics of the wave field and the surface mixed layer. Of particular interest has been the dissipation of surface wave energy by breaking.				
14. Subject Terms.  surface breaking waves, wave dissipation			15. Number of Pages.	
			16. Price Code.	
17. Security Classification of Report. Unclassified	18. Security Classification of This Page. Unclassified	19. Security Classification of Abstract. Unclassified		20. Limitation of Abstract. None

# **FINAL REPORT**

## **Measurements of Wave Breaking and Dissipation over the Continental Shelf**

W. Kendall Melville  
Scripps Institution of Oceanography  
University of California, San Diego  
La Jolla, CA 92093-0213

phone: (858) 534-0478 fax: (858) 534-7132 email: kmelville@ucsd.edu  
Award Number: N00014-97-1-0277 (2/1/97 – 1/31/02)  
<http://airsea.sio.ucsd.edu>

### **LONG-TERM GOALS**

The long-term goals of this research have been to quantify the incidence of surface wave breaking and its role in dissipating wave energy, which is then available to generate currents and turbulence in the upper ocean.

### **OBJECTIVES**

The objectives of this project were to develop and use remote and in situ techniques to measure the kinematics and dynamics of breaking and relate them to the dynamics of the wave field and the surface mixed layer. Of particular interest has been the dissipation of surface wave energy by breaking.

### **APPROACH**

The approach revolved around the use of aerial imaging from light aircraft in the coastal zone and quantitative image sequence analysis using techniques of Particle Imaging Velocimetry (PIV) to measure the kinematics of whitecaps. Kinematic measurements were used to investigate aspects of surface mixing including estimates of the rate of mixing of the surface layer. In conjunction with simple scaling arguments to relate the kinematics of breaking to the dynamics, and laboratory experiments on breaking, the remote data were used to investigate wave dissipation and the momentum flux from waves to currents. In situ measurements of waves and currents to compare with the remote measurements remains a topic of continuing research.

### **WORK COMPLETED**

This project has focused on the Shoaling Waves Experiment (SHOWEX) conducted off Duck, N. Carolina in the fall of 1999 with other supporting measurements off Oahu, Hawaii, and California. During SHOWEX our imaging system, the Modular Aerial Imaging System (MASS) was flown on the Long-EZ by Tim Crawford (deceased) of NOAA. Using the data acquired from that experiment we developed algorithms based on both PIV and simpler techniques to analyze the image sequences to measure  $\Lambda(c)$  dc, the mean length of breaking fronts per unit area of ocean traveling with speeds in the range  $(c, c+dc)$  (Phillips, 1985). This statistic forms the basis of a hierarchy of moments that can be

used to investigate the kinematics and dynamics of breaking. Figure 1 shows examples of the image data, the traditional whitecap coverage and an example of the PIV processing on a single whitecap.

Two moorings were deployed to measure near-surface turbulence (ADV and Dopbeam sensors) and temperature fields and bubbles entrained by breaking waves. Two bottom ADCP/pressure packages were deployed to measure waves and currents on the shelf. One mooring suffered a failure during a hurricane and was redeployed. One of the moorings was inexplicably destroyed by the Canadian Coast Guard vessel *Creed*, a participant in the experiment, during good weather with unlimited visibility.

## RESULTS

MASS data from SHOWEX has been analyzed, written up and published by Nature (Melville & Matusov, cover article, May 2, 2002). We have shown that during SHOWEX  $\Lambda(c)dc$  increases like the wind speed cubed,  $U_{10}^3$ , and decays exponentially with the breaker speed,  $c$ . Since the breaking statistics depend on the directional wave spectrum, and since there is no universal wave spectrum over the full range of breaking waves, we do not expect any universal shape for  $\Lambda(c)dc$ . Simple physical and dimensional arguments provide interpretations of the various moments of  $\Lambda(c)$ . For example, the first moment is proportional to the rate of mixing of the surface area by breaking, the third is proportional to the volume mixed, the fourth is proportional to the momentum flux from waves to currents and the fifth is proportional to the wave dissipation. These moments are shown in Figure 2. Note that as you move to higher moments the mode of the distribution moves to larger values of  $c$ . Since  $c$  scales approximately with the phase speed of the breaking waves, this implies that while small-scale waves contribute most to the length of the breaking fronts, longer waves are responsible for momentum transfer and dissipation. Since the vector  $\mathbf{c}$  and not just the speed are measured, we can examine the directional distribution of  $\Lambda(\mathbf{c})$  and its moments can be measured. Examples in Figure 3 show that for the SHOWEX data,  $\Lambda(\mathbf{c})$  and its moments are approximately symmetric about the wind direction.

The *in situ* data from the surface moorings shows that the dissipation of turbulent kinetic energy (TKE) measured by the Dopbeam correlates with the modulation of the surface waves or wave groups. An example of this data is shown in Figure 4. Analysis of the Dopbeam, ADV and temperature data continues.

## IMPACT/APPLICATIONS

During this project we have shown that methods of PIV developed in the laboratory can be used to analyze airborne imagery to measure the kinematics and, with supporting assumptions, the dynamics of wave breaking. These results are novel and are the consequence of the convergence of technical developments in the areas of imaging, position/motion detection (DGPS and inertial systems) and imaging software. While we have concentrated on visible imagery, the same approach could be taken with IR and hyperspectral imagery to study the kinematics of different fields including temperature.

The *in situ* data shows great promise for making acoustical measurements of ocean microstructure directly in the wavenumber domain (Veron & Melville, 1999). This avoids the use of Taylor's hypothesis to move from the frequency domain to wavenumber domain; an approach that has been fraught with problems in the surface wave zone which is dominated by the orbital motion of the waves.

## TRANSITIONS

The imaging system has been transitioned to the measurement of breaking and spray generation in hurricanes with support from ONR's CBLAST program.

## RELATED PROJECTS

Related projects are described on our web page at <http://airsea.sio.ucsd.edu>.

## REFERENCES

Phillips, O.M. 1985 Spectral and statistical properties of the equilibrium range in wind-generated gravity waves. *J. Fluid Mech.*, **156**, 505-531.

## GRADUATE THESES

### PhD:

**Eric J. Terrill**, Acoustic measurements of air entrainment by breaking waves. SIO/UCSD, 1998.

**Fabrice Veron**, Turbulent mixing at the surface of natural water bodies: breaking waves and Langmuir circulations. SIO/UCSD, 2000.

### MS:

**Ronan Gray**, Dissipation of turbulent kinetic energy in the surface-wave layer of the ocean. Mechanical and Aerospace Engineering, UCSD, 2001.

**Genevieve R. Lada**, A model of bubble transport and gas transfer in the nearshore. SIO/ UCSD, 2002.

## PUBLICATIONS

Veron\*, F. and W.K. Melville Pulse-to-pulse coherent Doppler measurements of waves and turbulence. *J. Atmos. Oceanic Tech.* **16**: 1580-1597 (1999).

Melville, W.K., C. White\*, F. Veron\*, and E. Luft\*. Laboratory measurements of turbulence under breaking waves. In: *Proc. Symp. on the Wind-Driven Air-Sea Interface*, Univ. of NSW, Sydney, M.L. Banner, ed., pp. 211-218, ADFA, Canberra (1999).

Melville, W.K. Surface Gravity and Capillary Waves. In *The Encyclopedia of Ocean Sciences*, J. Steele, S. Thorpe and K. Turekian, eds, Academic Press, pp 2916-2924 (2001).

Terrill, E.J., G. Lada\* and W.K. Melville, Surf zone bubble populations. *Acoustical Oceanography*, Vol 23, Part 2. pp. 212-219. Institute of Acoustics. Bath Univ. Press, Bath. U.K. (2001)

Melville, W.K. & Matusov, P. 2000 Measurements of the distribution of breaking waves at the ocean surface: a simple statistical description. *Nature*, 417, 58-63, & cover article, May, 2, 2002.

Young, I.R., M.L. Banner, M. Donelan, A. Babanin, W.K. Melville, F. Veron and C. McCormick, An Integrated Study of the Wind Wave Source Term Balance in Finite Depth Water. *J. Atmos. & Ocean. Tech.*, sub judice (2002).

Melville, W.K., F. Veron\* and C. White\*. The velocity field under breaking waves: Coherent structures and turbulence. *J. Fluid Mech.*, 454, 203-233 (2002).

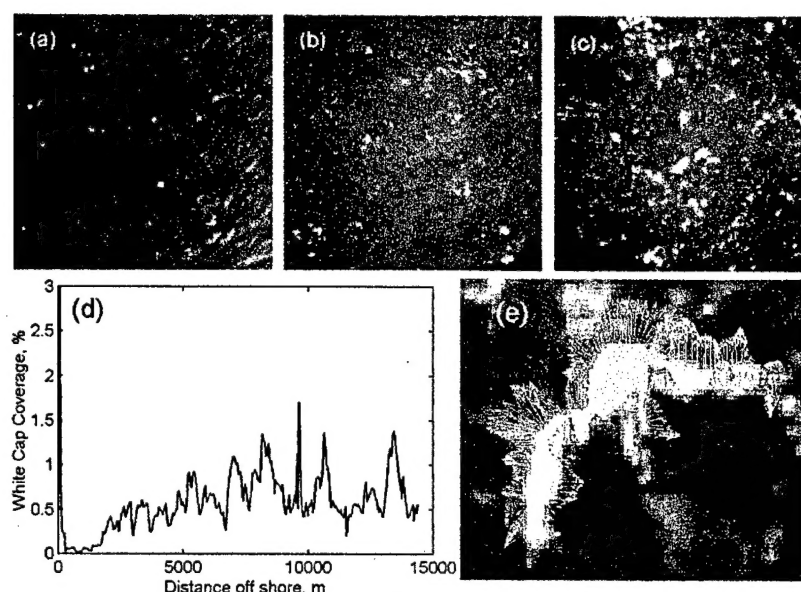


FIG. 1a-c: Images showing approximately 160 m x 160m of the sea surface for mean wind speeds,  $U_{10}$ , of 7.2, 9.8 and 13.6  $\text{m s}^{-1}$ , respectively, in SHOWEX. Note the increasing density of whitecaps with  $U_{10}$  and their random shapes. d Whitecap coverage as the aircraft flew offshore. Note the large fluctuations at spatial scales of  $O(1-10)$  km that may be due to both local wind and wave modulations. e: The result of processing a single whitecap using the PIV technique in which the normal velocity of the boundary of the whitecap is resolved.

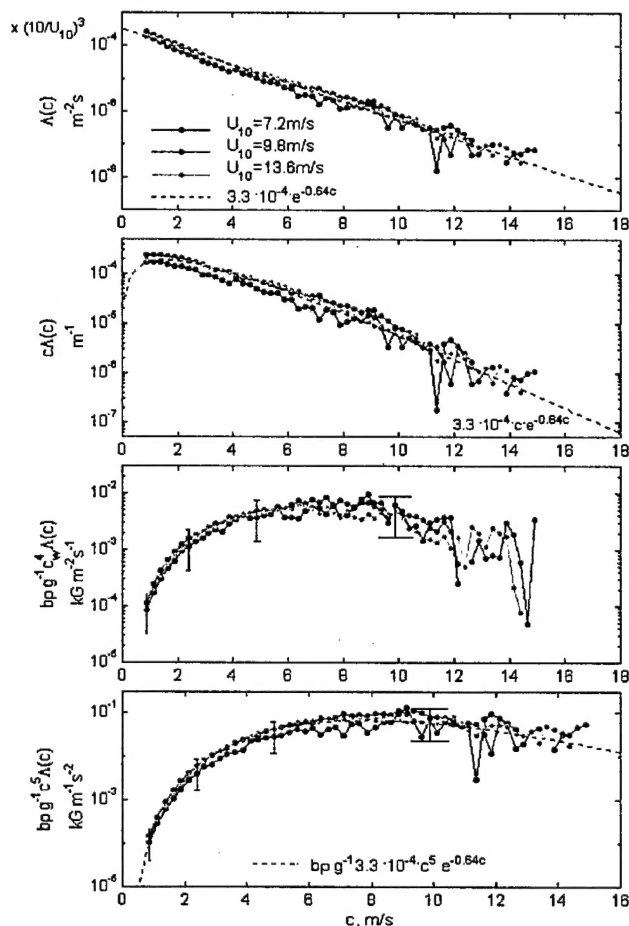


FIG. 2a, Binned measurements of  $\Lambda(c)$  weighted by  $U_{10}^{-3}$  showing that the average length of breaking fronts in  $(c, c+dc)$  per unit area of sea surface increases like  $U_{10}^3$  and decays exponentially with  $c$ :  $\Lambda(c) = 3.3 \times 10^{-4} \cdot e^{-0.64c}$ .

b. The weighted first moment of  $\Lambda(c)$  which corresponds to the fractional area swept out (turned over) by breakers in the speed range  $(c, c+dc)$  per unit time.

c. The weighted fourth moment of  $\Lambda(c)$ ,  $c^4 \Lambda(c)_w$ , which corresponds to the momentum flux from waves to currents due to whitecaps, with the subscript "w" referring to the component in the wind direction.

d. The weighted fifth moment of  $\Lambda(c)$ , which corresponds to the energy lost from the wave field due to breaking: "wave dissipation".

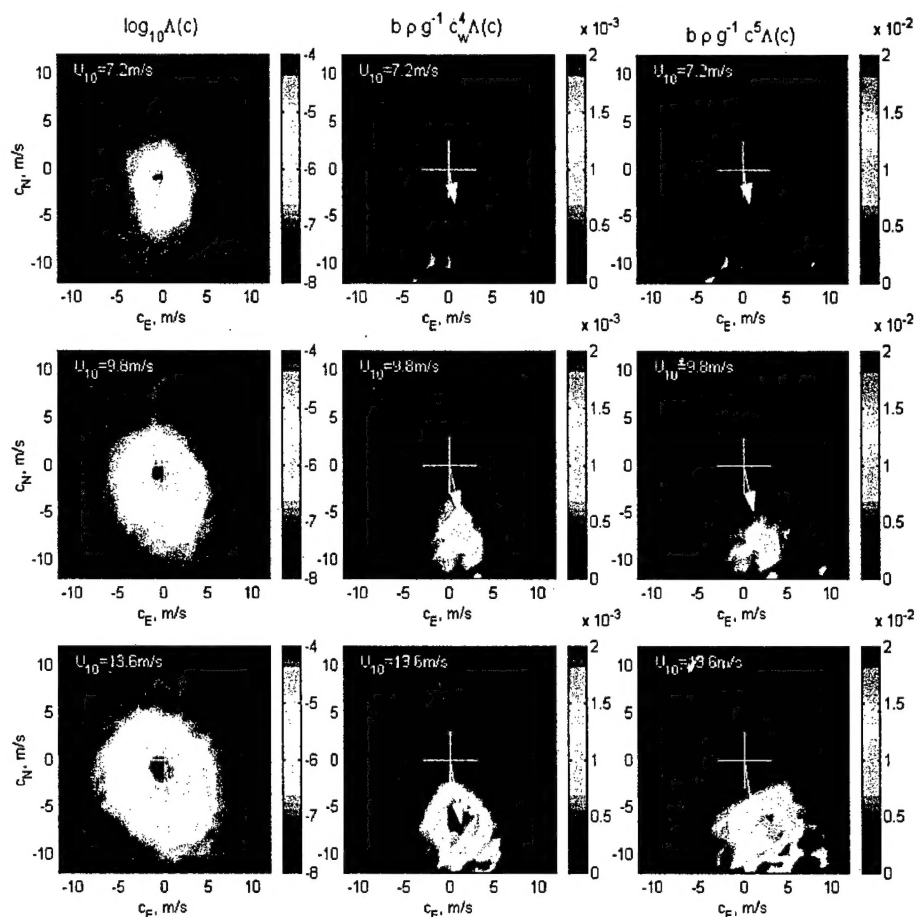


Figure 3a. Distributions of  $\Lambda(c)$ , with respect to the northerly and easterly components of  $c$  ( $c_N, c_E$ ), along with the average wind direction (arrow). Note that the dominant orientation is close to the wind direction.

b. The corresponding momentum flux from waves to currents due to breaking for the three wind-speeds. Note that as the wind increases the region of significant momentum flux becomes approximately symmetrical about the downwind direction (c.f. Fig. 2b).

c. The corresponding distribution of the dissipation with ( $c_N, c_E$ ).



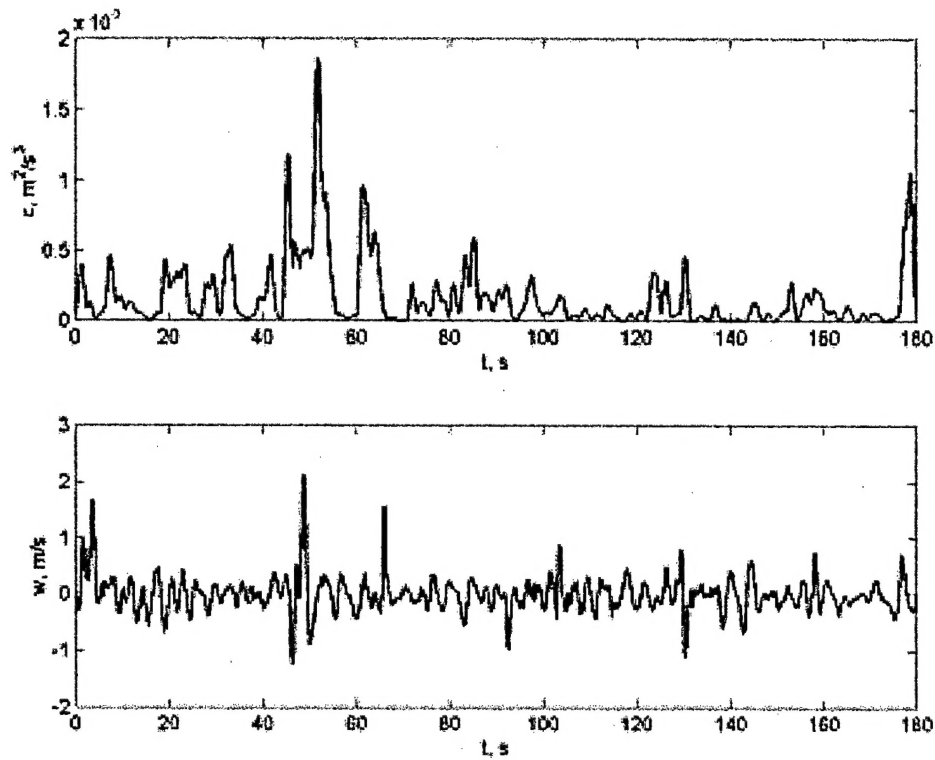


FIG.4. Top: Inertial estimates of dissipation from the Dopbeam acoustic Doppler near the surface in SHOWEX. Bottom: Simultaneous measurements of the vertical component of orbital velocity measured with an ADV on the same mooring. Note the correlation between the modulation of the wave field and the dissipation, especially around 45-50 s.